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MEDIUM SPEED ENGINE APPLICATION OF A PIEZO ELECTRIC ACTUATED FUEL INJECTION VALVE

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ABSTRACT

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Significant efforts are spent in the medium speed diesel engines industry to overcome the limitations encountered with solenoid actuated injection valves, which are not capable of modulating their operation but can only be forced to be fully open or fully closed. In parallel, research on piezo electric actuators begins to offer attractive products even for large engines applications. While some promising experimental result is achieved on standalone injectors, there is no system in place to test these performances on a real engine. The present work aims at filling this gap, by providing a study on how the experimental setup needs to be expanded in order to achieve its full integration in the existing Engine Automation and Control System.

The work is conducted in two parts, the first of them dealing with a study of the host system and of the experimental piezo driver to be integrated in it. In this part both systems are analysed and the features that are relevant in an integration perspective are explored in greater detail, providing all the necessary information in order to elaborate on the subsequent steps, with special focus on the identification and prioritisation of the requirements. The second part consists of the engineering of an upgraded system, where the host environment is equipped with all the functionalities needed to support the piezo electric actuated injectors. This part elaborates from the considerations on the general technical aspects that have to be addressed, in order to define and explain the strategic choices deriving from them, also based on the target working environment. Among the results are the designs of the power supply architecture and of the control logic handling the most important functions of the piezo driver.

CONTENT

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ABBREVIATIONS

CCM	Cylinder Control Module
CFD	Computational Fluid Dynamics
CR	Common Rail
DAC	Digital to Analog Converter
EFIC	Electronic Fuel Injection Control
EOI	End of Injection (signal)
ESM	Engine Safety Module
FET	Field Effect Transistor
HP	High Pressure
I/O	Input / Output
LCP	Local Control Panel
LDU	Local Display Unit

MCM	Main Control Module
MFI	Main Fuel Injection
PC	Personal Computer
PCB	Printed Circuit Board
PDM	Power Distribution Module
PWM	Pulse Width Modulation
RPM	Revolutions per Minute
SOI	Start of Injection
TDC	Top Dead Centre
TTL	Transistor-Transistor Logic
UNIC	UNIfied Control
VAC	Alternating Current Voltage
VDC	Direct Current Voltage

1 INTRODUCTION

1.1 Objectives and outline of the present thesis work

The present work provides a target-oriented digestion of the information and the data available on two different and independent fields of knowledge, and utilises the outcome of this process as a starting point for the development of a novel technical solution that merges the both.

Two systems are considered, separately at first: they are an experimental control system where research is conducted on the possible application of piezo electric actuators in medium speed diesel engines, and the engine automation and control system currently in use in the engines manufactured by Wärtsilä, the company that commissioned this work.

After the introductory part of Chapter 1, where the necessary background is provided, the information pertaining to each system and that is relevant to the scope of this project is systematically selected, summarised and classified, and in this way it is presented in Chapter 2 - for the part concerning the experimental control system - and in Chapter 3, for what is to be discussed about the Wärtsilä engine automation system.

Although no new knowledge is generated in these two chapters, they have been compiled upon an explicit request of the commissioning Company, based on the fact that the amount of documentation available for each of these systems is very extensive and, furthermore, this documentation is available not from only one but from several different sources. In this context, the Author’s work consists of the analysis of all sources in order to narrow the resulting documentation package down to what is strictly functional to the project’s target, and to organise it in a systematic arrangement in order to facilitate its further use.

Chapter 4 differs from the more descriptive Chapters 2 and 3 as it consists of a set of considerations that together represent the initial design stages of a completely new system. The chapter explores a number of technical solutions to enable the integration of the piezoelectric actuated fuel injection valve, previously studied only as a single component within a test rig, into the more complex context of a working diesel engine. More specifically, the chapter addresses the integration of the experimental control system described in Chapter 2 into the engine automation system environment described in Chapter 3.

The ultimate result of the present work is a solution proposal describing the necessary modifications to an existing engine automation system in order to support the use of piezoelectric actuated fuel injection valves instead of conventional solenoid actuated injectors. This proposal is obtained by selecting and combining the best options for each of the aspects considered.

However, in the context of Chapter 4, the commissioning Company not only requires the definition of a final solution proposal, but also requires that analysis of the alternative approaches to each of the aspects addressed is included, as it anyway represents a relevant part of the presented Author's work - and documentation about it should exist for future reference.

To complete the outline of the present work, Chapters 4 also deals with the conclusions summarising the solutions selected for a first stage of deployment and the reasons why they have been selected among the alternatives proposed. The discussion continues with the solution that are planned to be perfected and rolled out in a subsequent stage of development. In the last part the reader can find a summary of the improvements that is already possible to foresee for the generations of controllers to come.

1.1.1 Background of the research that has lead to this project

Piezoelectric injectors for diesel engines are a concrete reality in the automotive segment, where the sizes and the forces involved make these components a suitable alternative to the solenoid actuators that have dominated the market in the past decades. However, when it comes to medium-large or large diesel engines, the scenario is substantially different: fast microcontroller based ECUs (Electronic Control Units) enable common rail systems to achieve precisions that were unthinkable with conventional mechanical control systems, and this great advantage has been exploited in all possible ways and has led manufactures to come up with engines that truly reach state of the art in terms of efficiency and emission levels. But while the technology gets closer to its limits, the push on research for new, better solutions does not ease; on the contrary, it keeps strong, with always more stringent emission legislations upcoming [1] and a fierce competition for the market constantly on.

This has forced researchers to start looking into the areas where the technology limitations could be overcome. One area that promises great margins of improvement is the control over the fuel injection rate shape: the possibility of finely modulate the injection event opens up a large territory to explore. Partial knowledge is derived from the smaller scale automotive engines, and computer simulations of CFD (Computational Fluid Dynamics) models support the theories promoting this approach, but the actual research in this territory is only at its dawn.

What substantially prevents current diesel injectors from fully entering the domain of injection rate shaping, is the physical limitation of their actuators to a mere on/off functionality. This is primarily due to the essential nature of solenoids and how they are constructed: although they are capable of generating the forces required and their responses in time are sufficiently fast, they can only be operated in two states and therefore a valve connected to them can be only controlled to be open or closed. Some attempts to control the transients between these two states of the mechanical output have been made by various modulation techniques of the electrical input signals, but the results of these experiments were poorly usable in practical applications. Furthermore, the solenoid does not directly drive the lifting of the needle valve that causes the fuel to be sprayed from the injector, but it only acts as a controller of a more complex hydraulic system where the displacement and the force are amplified to the levels necessary to correctly operate the needle.

Piezoelectric actuators, on the other end, provide their mechanical output in form of a displacement which is continuously proportional to their electrical input. The research for their application as direct injection controllers for these sizes of injectors, however, has not been possible earlier than in these years, due to the fact that their technology was not mature enough to provide sufficient forces, speeds and displacements. However this is changing now, as these components and their capabilities continue to develop, making the piezoelectric actuation an extremely interesting candidate for the fuel injection systems of the future.

1.2 Piezo electric actuation

The piezoelectric effect occurs in certain materials, which are known as piezoelectric materials, whenever a mechanical strain is applied to them. The result is that a certain amount of electricity is generated by the material itself.

The phenomenon is based on physical and electrical interactions at the molecular level of such materials – typically crystals or ceramics – and four of its two most important characteristics are:

- Reversibility: a physical strain applied to the material generates a voltage in the same way as the application of electricity generates a physical deformation of the material. The latter is known as the converse piezoelectric effect and the applications of piezoelectric materials as actuators are based on it.

- Linearity: the instantaneous amount of generated electricity is directly proportional to the applied mechanical strain or, when considering the converse effect, the physical deformation is directly proportional to the applied voltage.

- Fast reaction: the reaction time, intended as the time that elapses between the moment when electricity is applied and the moment when an effect on the physical structure can be observed, is in the order of the microseconds. The phenomenon is also characterised by high acceleration rates, which cause the induced material deformation to complete within time ranges of the same order of magnitude of the reaction time.

- High resolution: the displacement of a piezoelectric actuator can be controlled very precisely by controlling the voltage applied to it. With certain constructions of the piezoelectric component, subnanometer precisions can be achieved - making this technology very appealing for a wide range of super high precision applications like for example in the fields of medical, aerospace and nanotechnology.

Although different actuator constructions exist, focus will be kept on the so called ring actuators, as they are used as a base for the application on the piezoelectric injector. Other common types are plate (the plate thickness varies linearly with the applied voltage) and plate benders (a bar that bends proportionally to the applied voltage).

Figure 1 - Ring actuator

The form of a ring actuator is shown in Figure 1 here above and a typical thickness for this ring could be for example 2mm, while the outer diameter could range from about 6 to 20mm. It is possible, however, to obtain actuators manufactured according to customer-specified dimensions, whenever other aspects of the system where they are intended to be used prevents the choice of an anyway wide and growing range of catalogue sizes.

The displacement in this kind of actuators occurs along the centreline of the component, resulting in a variable (electrically controllable) thickness of it.

1.2.1 Piezo actuator stacking

It has to be noted that the maximum displacement achievable with one single ring actuator is relatively little compared to the ring's thickness itself, typically less than 1%. This means that to achieve a sufficient displacement for the direct actuation of an injector's needle (see also Paragraph 1.2.2), which targets displacements in the range of 1 to 2 millimetres, a very thick element would be needed.

Due to the manufacturing limitations posed by the physical-electrical characteristics of the piezoelectric material, however, only a limited range of thicknesses and form (diameter to thickness) ratios are available, and suitable elements for the application presented in this work are only found in thicknesses of about 2 to 3 millimetres.

Nevertheless, it is possible to pile up several of these discs, one on top of another, and by doing so create what is known as a piezo-stack. All discs are electrically connected so that they are energised at the same time, and the behaviour of the piezo stack as an actuator is the result of the cumulative effect of each element's displacement.

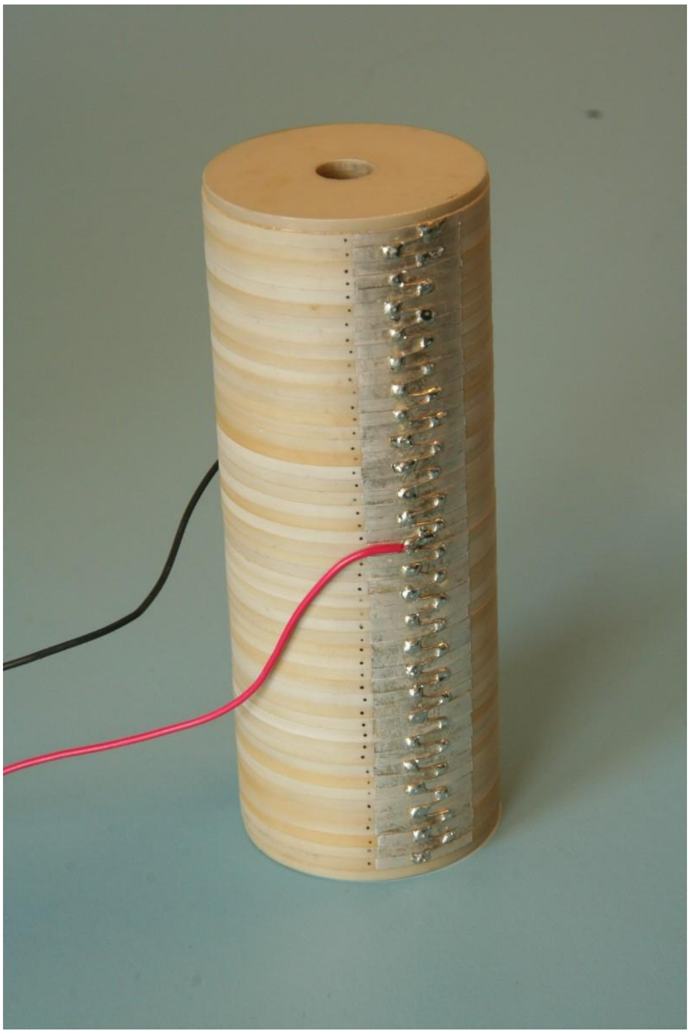

Figure 2 – A piezo-stack

1.2.2 Direct acting principle

Injectors that are actuated by solenoids normally need to feature a displacement amplifier in order to transform the little movement of a solenoid shaft (typically a few tens of a millimetre) into the required needle lift. This displacement amplifier is typically implemented by a conveniently arranged hydraulic circuit, making use of an additional line of pressurised control oil for example.

Drawbacks of this solution are in general the increased complexity of the injector design, manufacturing and construction, and the delays introduced along the control chain from the actuator to the needle. This is necessary though when using a solenoid, but having a piezo stack that is by itself capable of producing the required displacements with suitable forces and speeds, obviously made the direct actuation (of the needle) an attractive path to pursue. Furthermore, and differently than with solenoids that only offer an on/off control capability, the displacement of the piezo stack actuation can be truly modulated by modulating the electrical input signal. This means that by direct actuation, by the modulation of the electrical input signal it is possible to actually modulate the injector's needle movements, without any of the delays and uncertainties deriving from the intermediate steps typical of solenoid based controls.

2 EXPERIMENTAL CONTROL SYSTEM

This chapter gives an overview and points out the most relevant aspects of the *piezoelectric actuated injection valve* test rig that has been built at Aalto University of Technology within the scope of the technology development project described in Paragraph 1.1.1

Focus is kept on the deployment of the electronics used to drive the piezo electric actuator itself, and that are hereby referred to as the “experimental control system” or more specifically the “control unit”. This control unit combines a microcontroller application for driving the piezo electric actuator with the high voltage power stage for providing the needed voltage and current levels, and it represents the object of the integration proposed as the core of this thesis work (Chapter 0).

2.1 Test rig arrangement

See *Attachment 1.*

2.2 Control unit

The control unit can be functionally divided in two main stages: the actual control logic and the amplifier.

The controller stage is based on a 32-bit microcontroller. This provides a digital representation of the desired signal as a function of time, coordinating the timing for the start of each injection as well as the durations and trends based on the provided injection maps (see Paragraph 2.3).

See *Attachment 2.*

2.2.1 Development

The control unit as it was conceived in its first version can be seen in the attachments (*Attachment 2, Paragraph 2.1*). In this version, the rate shapes of the desired injection maps can be fed as pre-programmed waveforms from a separate microcontroller or function generator. What poses a major performance limit in this layout is the open loop operation, since no feedback from the piezo stack is provided to adjust the signals sent to it based on the actual effects that they generate. Furthermore, the potential for reducing the amount of analog signals between blocks has been identified: red arrows in the figure below denote the unnecessary analog signals which are prone to pickup noise, while green arrows denote digital signals which are favourable for achieving a cleaner output.

Collecting all the desirable improvements identified in the previous experience, a second version of the controller was made, and its concept layout can be seen in the attachments (*Attachment 2, Paragraph 2.1*). This time, a *state space representation* based controller has been implemented, as current and voltage measurements on the piezo stack are provided as feedback to the microcontroller for adjusting its output. In this algorithm the microcontroller is programmed, among other things, to compute first order integrals of the terms representing the deviation between desired and actual voltages and currents at every cycle. The mathematical representation of the control signal u is expressed by the formula below:

$$u = (U_{set} - U_{meas}) * K_{pU} + \int (U_{set} - U_{meas})dt * K_{iU} \dots$$

$$+ (I_{set} - I_{meas}) * K_{pI} + \int (I_{set} - I_{meas})dt * K_{iI} \ ,$$

where: U_{set} is the target voltage, U_{meas} is the measured voltage, I_{set} and I_{meas} are target and measured currents respectively, and K_{pU}, K_{iU}, K_{pI} and K_{iI} are correction factors.

This approach lead to satisfactory results in terms of waveform control performance (both current and voltage) but some other issues remain to be addressed, such as the noise problems due to non optimised layout and design, that prevented operation at high voltages, or the PWM modulator that could be synchronized with measurements in order to reduce switching noise considerably.

See *Attachment 2.*

2.2.2 Power supply

The piezo amplifier needs an input power of around 15-20 Watts. To be on the safe side and to avoid operation near the physical limits of the power supply unit, a 50 W unit should be recommended.

The present amplifier needs separate 1000V supply for driving the piezo stack and +/-15V logic power supply for the controller and the other circuitry. By implementing the necessary adapters, the power could be supplied to the amplifier with 24 VDC or 230 VAC or with some other DC voltage based on availability.

The input current depends of course on the voltage level; anyway in peak conditions (the transient when the piezo stack is energised) the measured current levels did not exceed 50mA.

2.3 Injection maps

The injection rate shapes can be provided by an external function generator, or pre-programmed into the microcontroller firmware, or else they can be software generated. Regardless of their origin, this paragraph gives a brief overview of the shapes of the waveforms that are considered to be desirable and beneficial from the engine performance point of view. It is the final objective of the piezo electric actuated injector, to produce a spray jet that closely resembles these forms in the combustion chamber of each cylinder.

At the controller's present stage of development, the injection maps are pre-programmed into the microcontroller firmware. In practise, the requested shape (see Figure 3 to Figure 6 in this paragraph) is written in form of a MathLAB expression, and then a separate MathLAB algorithm is applied to the waveform expression in order to generate its data points, which are then stored as a vector in the microcontroller's memory.

Samples are read at an adjustable frequency (at the moment is 40 kHz) which is generated by one of the microcontroller's timer interrupts. This frequency can be adjusted between 1 Hz up to several hundreds of kHz, but it is unnecessary to have frequencies higher than the PWM switching frequency, which is 100 kHz.

The frequency adjustment is done by changing the values that are combined to obtain the frequency division factor of the timer interrupt used, and the frequency can be selected with a precision of 1Hz. In practise this means that it is possible to achieve a step from one initial frequency of for example 40 kHz to an updated frequency of 40001 Hz if increasing, or of 39999 Hz if decreasing.

The map only considers the active part of the injection, not the whole period between two consecutive injections, because the non active part of the cycle has varying durations depending on the number of cylinders considered for each specific engine, while the active part should be defined uniquely for all applications. Besides, there would be only zeros anyway in the areas between two injections, making the datapoints of the non active part not worth using memory space to be represented.

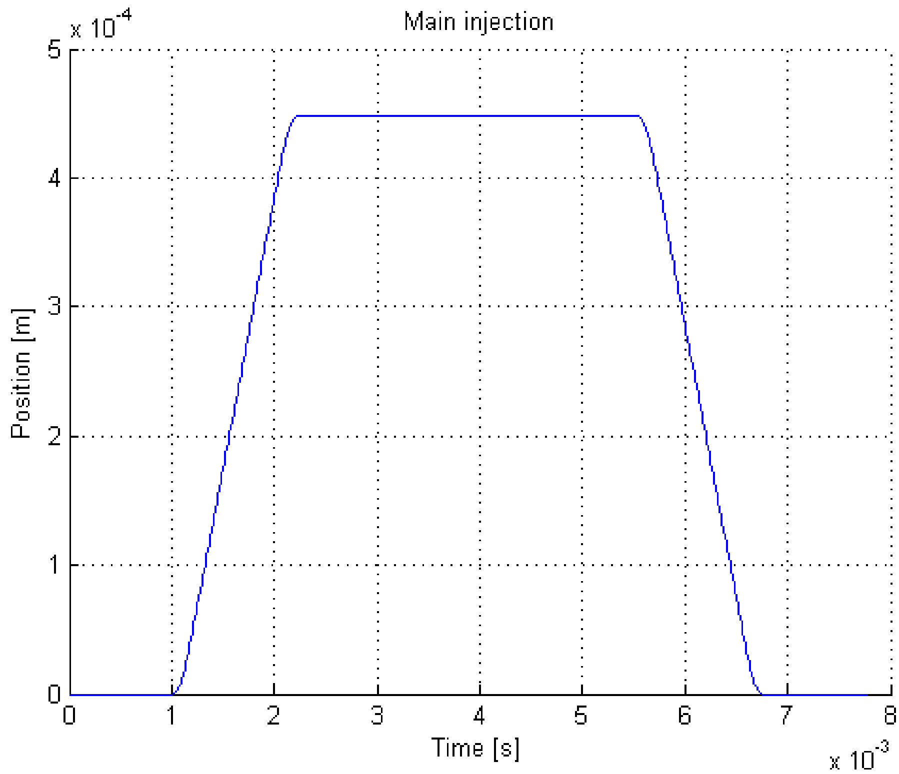

Figure 3 - Square injection rate shape

The figure above shows the first of the control signals that have been given to the developers of the experimental control unit and it represents the most basic requirement: a simple on-off capability with reasonably steep rising and falling edges. The total duration considered is about 6 ms, a value that can be considered very well representative of what a normal duration could be during engine operation. Considerations of this kind will be used as a base for further development in Paragraph 4.3.

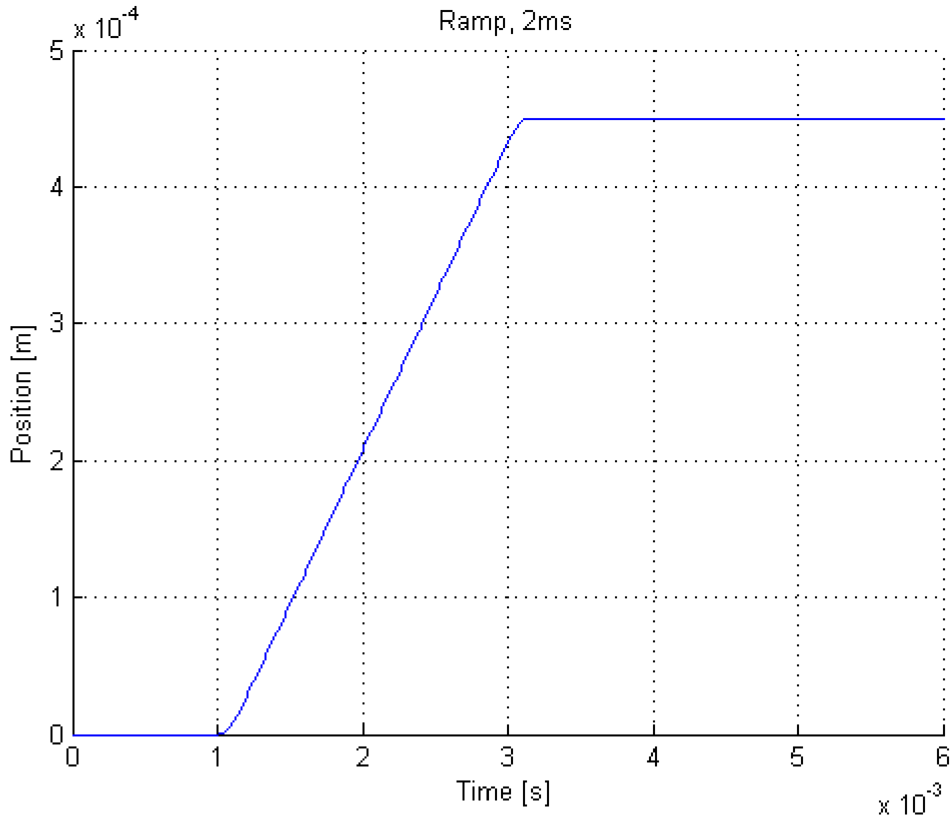

Figure 4 - Ramp injection rate shape

The ramp of Figure 4 is not an actual required injection rate shape, but it has been submitted to the developers of the experimental control unit as a support for conducting research and for collecting knowledge specifically about the behaviour of slopes (a rising edge in this case) and how to control them.

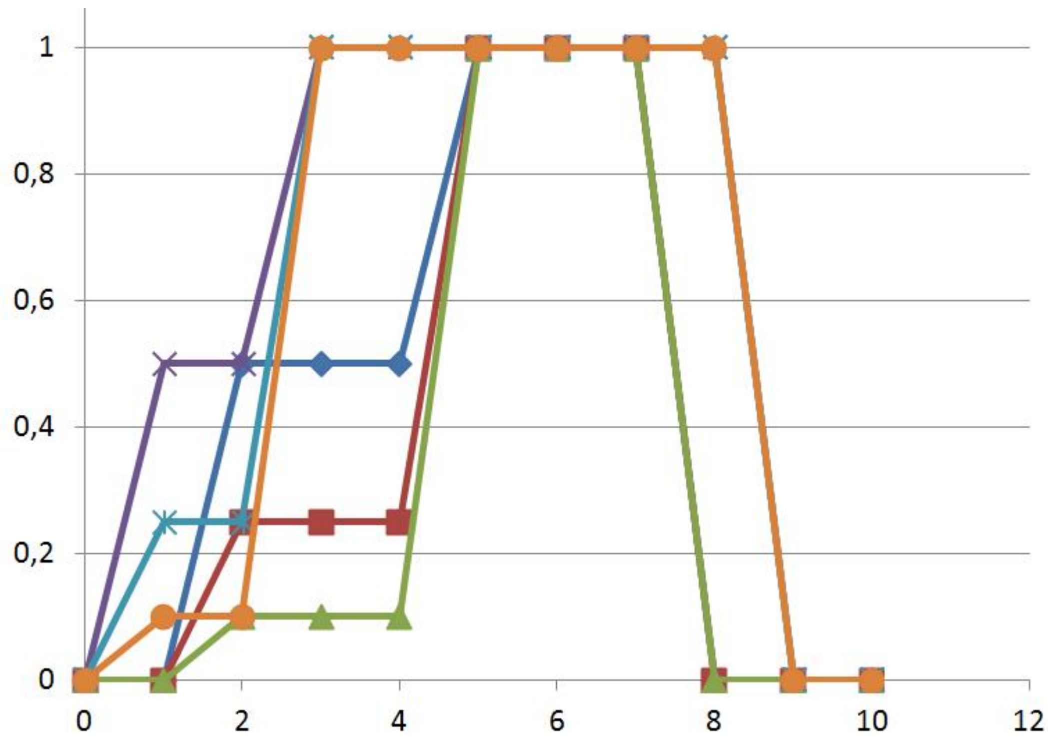

Figure 5 - "Boot" injection rate shape

Figure 5 shows what has been called a boot shape. In such a shape the injection event is divided in two consecutive parts. In the first part, which lasts only a percentage of the total duration, the pressure is kept at a value significantly below the maximum pressure. In the second part, the pressure is raised and kept to the maximum level until the end of the injection. It is easy to understand that different shapes of boots can be achieved. In Figure 5, for example, it is already possible to recognize 6 different tracks, resulting from different durations of the first part compared to the total duration that is then reached with the second part, and from different amplitudes of the first part compared to the total amplitude, that is then reached in the second part. Boot shapes have been investigated earlier with other research tools and they have been proven noticeably advantageous from the combustion point of view, yielding to consumption and NOx figures that are more than competitive with those that are normally achievable with solenoids.

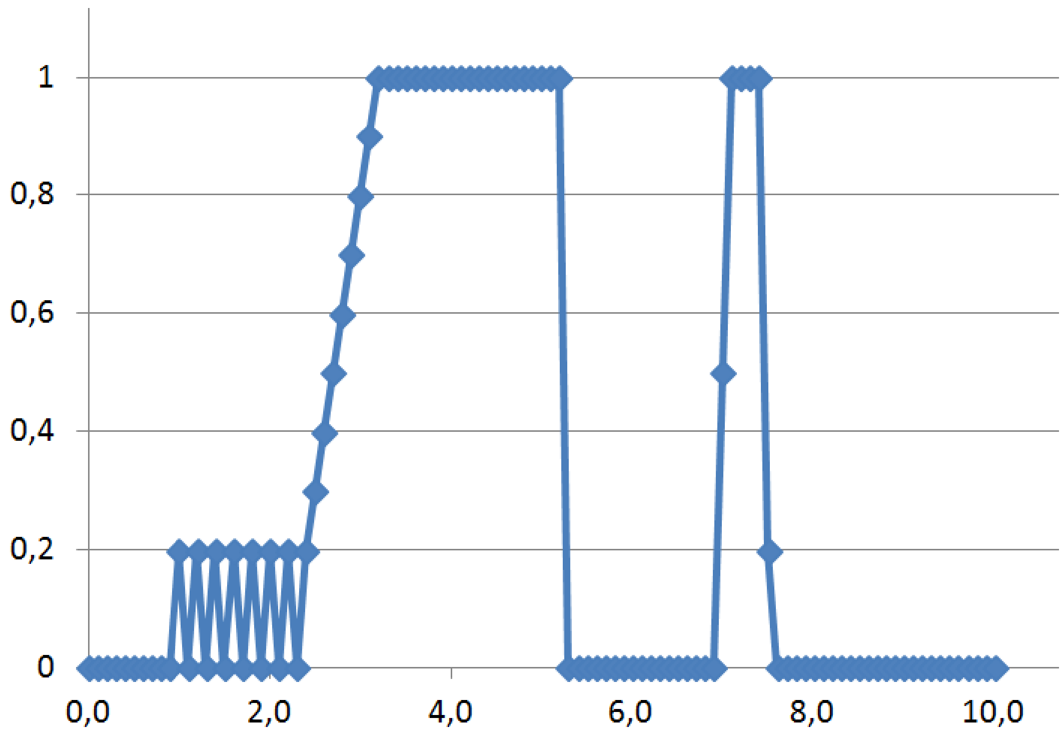

Figure 6 - Example of pilot-train + main + post injection

In Figure 6 we can observe an injection rate shape that is normally used in today's passenger cars equipped with common rail diesel engines. The train of small pilot injections sets up an ideal environment for the main combustion to begin and being then fed with the fuel provided in the main injection, before being shortly cut and then provided again at full pressure in a last, short shot rewarded as the post injection. Not only this kind of shape gives very low NOx figures, but also allows the engine to achieve a smooth but still fully efficient combustion. This also has positive effect to the overall noise and vibrations generated.

2.4 Experimental results

See *Attachment 3*.

2.5 Conclusions

Although the introduction of the feedback feature brought a significant improvement in the performance of the controller, there still are some hardware issues that could not be overcome by adjustments or modifications to the present layout, such as the switching noise that prevents the unit to work correctly in the higher band of its operating voltage range. The results achieved are acceptable but have wide margin for improvement. In order to achieve better results, a completely new version needs to be engineered, without DAC and analog circuitry. Work on this new version is currently in progress.

3 ENGINE AUTOMATION SYSTEM

In this chapter a description of the Wärtsilä Engine Automation and Control System is given, being the engine the ultimate environment where the *piezoelectric actuated injection valve* is intended to be operated, and therefore being the engine's automation system the hosting platform for the piezo-injector controller to be integrated to.

As the system in its whole is a very articulated and technologically advanced work of several different fields of engineering, focus is kept on the features that are significantly relevant from the project target standpoint. Those consist of a combination of selected hardware modules, communication protocols, control algorithms and architectural arrangements that are determinant for the *piezoelectric actuated injection valve* to be integrated.

It follows that, after overviews of the system architecture and general arrangement descriptions are given, the scope of this chapter narrows down to specifically address the fuel injection control features of the engine automation.

The information provided constitutes the base on top of which the integration of the experimental control system into the engine environment is designed.

3.1 UNIC System architecture

One of the most noticeable characteristics of the Wärtsilä UNIC electronic control system is the capacity of the system to support different applications. This is achieved thanks to the scalable structure of the system architecture, which makes it truly configurable for any engine type, of any size and at any desired level of automation: from systems providing the basic safety features only, to the most inclusive ones featuring advanced controls, diagnostics and communication tools.

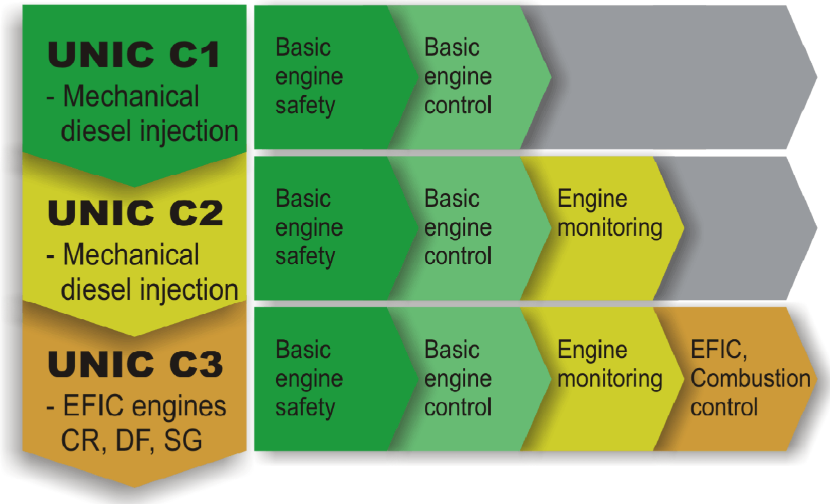

Figure 7 – UNIC Modules scalability concept

Three different system variants (UNIC C1, C2 and C3) provide coverage for the different engine types, and as the complexity increases, the automation system is expanded with the needed hardware and software in order to provide the required functionalities.

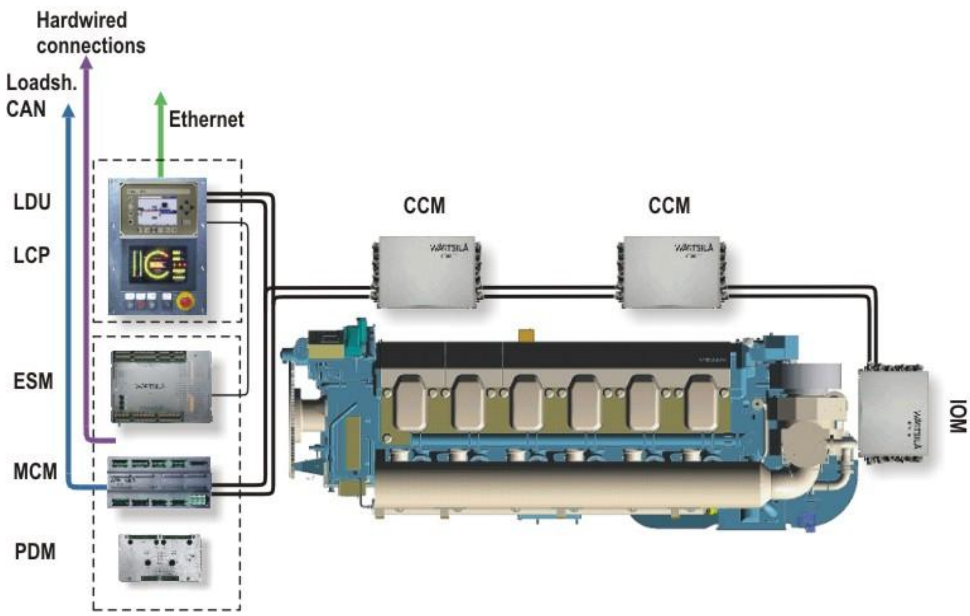

Figure 8 – Configuration of the modules of a UNIC C3 system

Figure 8 shows a typical deployment of the UNIC C3 automation system on a EFIC diesel engine like for example a Common Rail engine.

3.2 Power supply

The UNIC uses a power supply philosophy that differs from a conventional supply principle as it uses two separated power buses that provide redundant supply through the entire system with independent circuitries for “system” line and “driver” line. Voltage monitoring in all modules enables easy faults detection.

See *Attachment 4.*

3.3 UNIC C3 features for EFIC engines

The control strategy depends on the engine type; in fact, this is one major expression of the UNIC system’s versatility. Different types of EFIC engines are supported by the UNIC C3, namely SG (Spark Gas, gas engines working on the Otto cycle), DF (Dual Fuel, engines equipped with two separate injection systems, one of them being a gas system), and CR (Common Rail engines).

In case of Common Rail engines, the UNIC C3 provides the algorithms to control the fuel injection, using maps and other strategies to optimise the engine performances in different operating conditions, with different fuels.

3.4 CCM20 specific injector control features

The following paragraphs provide a description of the module and its features, with specific focus on the control of the fuel injection on Common Rail engine type, as this type is used as a base for the system integration presented in this work.

3.4.1 CCM20 module general description

The CCM (Cylinder Control Module) is the most representative feature of the UNIC’s automation level C3, which specifically addresses EFIC (Electronic Fuel Injection Control) engine types, and it serves as a cylinder controller in all current Wärtsilä applications where the UNIC C3 system is applied. In addition to the EFIC functionality the unit also features a range of inputs and outputs for miscellaneous purposes, mainly related to cylinder/combustion specific functions on the engine.

3.4.2 Control of the injection event

The CCM20 normally handles 3 consecutive injectors of the same bank of the engine. It follows that 2 modules are required for 4 and 6 cylinders engines configurations, while 8 and 9 cylinders engines require 3 modules and in case of Vee-engines the same logic is applied at each bank. Each injector is equipped with a solenoid acting as an electro-hydraulic actuator, and each solenoid is controlled by one channel of the CCM20's driver stage that is described in greater detail in the attachments (see *Attachment 5*).

Each solenoid is controlled by the algorithms featured within the engine automation system in order to produce the injection event *when* and *how* it is required for an optimised engine operation. In this context, the engine operation is optimised in terms of:

- Engine control – The engine is running at the desired speed, i.e. adapting its output power based on the load applied.
- Fuel consumption - The amount of fuel necessary to provide the required engine output is provided without unnecessary excess fuel.
- Emissions – The amount of undesired by-products present in the exhaust gases is minimised by achieving the best possible combination of the factors that have an influence on the combustion.

The two parameters controlling *when* and *how* the injection takes place in terms of electrical signals are the injection timing and the injection quantity and both are handled within the UNIC C3 function "Main fuel injection control", that is explained in greater detail in Paragraph 0 and its subparagraphs.

The Main fuel injection demand control defines the relevant fuel demand (= fuel injection quantity) and the Main fuel injection timing control defines when the quantity that will be injected. This information is then passed on to the Injection control.

See *Attachment 5.*

3.5 Control software

3.5.1 Software platform architecture

The software platform is designed with a layer approach: at the bottom there is the system software, which runs the low level system services, like for example I/O operations, time management, memory handling etc.

On top of this layer, a library of so called “engine functionalities” is built. These software application modules handle the actual engine operation algorithms, and as the name suggests each of them relates to a specific engine function. For each engine type only the needed modules are picked, and this selection together with other specific data (such as information on the control modules, parameters and maps definitions, partitioning and communication details) forms the so called configuration, from which the software package is in turn generated. The way software libraries are organised is represented in Figure 9 here below.

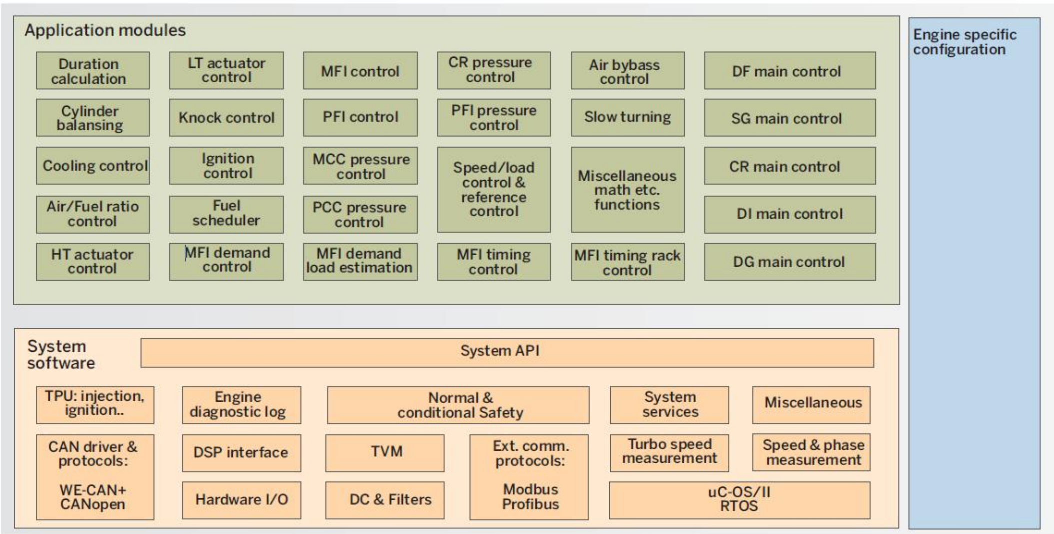

Figure 9 - Software library structure

The development of the software modules is carried out with advanced simulation tools that allow the software specialists to model and simulate the intended functions until the desired results are fully achieved.

It should be mentioned, however, that the maps and the parameters used by the functionality modules mentioned above are completely independent from the software itself. This means that these operating variables can be provided separately on a case-by-case basis (for example to adapt to different fuel characteristics) and can be easily changed without intervention on the software that operates on them.

In the functionalities library described above one function called "Main fuel injection control" handles the algorithms necessary to manage the computations for the fuel demand (fuel injection quantity) and for the injection timing at hand. From this function, the appropriate subfunctions are activated, depending on the specific engine type and on its current operation mode

See *Attachment 6.*

4 INTEGRATION OF THE NEW CONTROL SYSTEM

This chapter aims at identifying a convenient approach for combining the control system described in Chapter 2 with the actual engine automation system described in Chapter 3 in order to provide an engine where piezoelectric actuated injectors are installed, with an automation arrangement suitable to operate it.

To accomplish this task, the specific issues to resolve are identified and each is considered separately, analysing in detail the need and a number of options that would fulfil it. System features that are in the scope of this procedure are the power supply, the actual control strategy and the communications needs or, in other words, the ways in which the necessary information is exchanged between the existing and the added units.

In a subsequent stage, the technical solutions are analysed in their combinations rather than individually, in order to select the most convenient for the system rather than simply the best among the available alternatives.

4.1 Target engine type

The flexibility of the Unic system for an automation offer that covers the whole Wärtsilä engines portfolio should be reflected in the final solution that the present work helps at pointing to. This can and will be done, but a more cautious approach is preferable for the first considerations and analysis. The selection of a specific engine type to address at first, for example, would significantly limit the amount of information to be considered during the design phase, and at the same time would enable more agile changes and adjustments even at later stages like for example during engine tests.

For this reason, and also following some practical considerations, the smallest platform and configuration has been identified as an ideal ground where to start from: the W20-CR in a 4 cylinders in-line version. This means that the numerical values chosen to present the solution proposals in the following parts of this Chapter will be representative of values that are suitable for the W20CR engine.

Thanks to the scalability of the Unic system, a concept that is proven working can be easily expanded to cover a larger range of products in a later stage.

4.2 Power supply

The power supply for the control unit and for the piezo stack driver has to be arranged with regard to certain fundamental requirements that might determine the suitability of a particular solution only for a specific environment type. Based on this, it is possible to consider different arrangements in the perspective of different target applications, which for example may be power plants, marine applications or simple laboratory tests.

4.2.1 Requirements

The approach chosen for obtaining a definition of the power supply for the units that have to be added to the engine is to first collect the set of requirements and considerations to identify the power supply features that are necessary and to differentiate them from those that are installation dependent, that require additional research or efforts, or that are only nice to have but not strictly necessary. Only after this first research it is possible to sensibly begin a circumstantial solution design.

4.2.2 Control system - Electrical requirements

The microcontroller and its accessory circuitry is designed to work with a dual voltage DC supply of ±15V and currents drawn are reasonably low, considering that this section is only powering up the controller’s logic and eventually some part of the appended instrumentation, like for example the active laser sensor that in the current version of the controller provides feedback about the instantaneous displacement of the piezo stack. The whole low voltage logic does not constitute a problem anyway, since both the voltage and the current figures are lower than those of the any neighbouring Unic module.

A different situation presents itself regarding the power supply needs for the driver of the piezo stack, which - as already discussed in Paragraph 0 - requires DC voltages of 1000V. Nevertheless, the nature of the operation of the piezo stack is mostly impulsive and the duty cycles considered are relatively low (deriving from long intervals between pulses compared to the pulses themselves), and therefore the average power is considerably lower if compared with a system with similar electrical requirements but with a continuous mode of operation.

All in all, a power supply of 50W for the low voltage logic section and a power supply of 100W for the high voltage piezo drive would satisfy all the requirements without entering any stress condition due to working near the operational limits.

4.2.3 External power supply strategy alternative

The 24VDC power supply that powers the Unic is perfectly capable of handling the logic stage requirement, while some additional considerations are necessary for the 1000 volts section.

In a first instance it would appear convenient to arrange a separate power supply source for the 1000V, as this would generate substantial simplification of the adaptation work presented in this thesis. This implementation would require an externally generated and stabilised supply to be directly connected to the driver section of the piezo stack controller. There are commercially available off-the-shelf industrial solutions for this kind of need, and there is also a wide range of laboratory equipment capable of providing the required figures.

While this solution would be ideal for a laboratory environment where development of this integration system is conducted, it would be not as well advantageous in the industrial setting where the engine is intended to be located. This is because, regardless of whether the installation is in a power plant or in a vessel, the engine room is already providing all the systems necessary to the engine functioning and the connections to interface them to the engine itself. These include water supplies and return lines, lubricating oil and fuel connections to and from the respective tanks, and not least important, all the electrical power supply.

Besides of the need to arrange an additional external power supply, there would be another relevant drawback which is constituted by the by-passing of the Unic voltage monitoring features and the safety implementations that are related to them.

4.2.4 Solution with integrated DC-DC converters

In order to overcome the issues discussed in Paragraph 4.2.3 and to devise a system that does not depend on any additional external arrangement, it would be favourable to develop a solution with a module that can simply be included in the automation system configuration. This approach would also be coherent with the scalability and expansibility concepts that characterises the Unic automation systems (see Paragraph 3.1).

See *Attachment 7.*

4.3 **Control of the injection quantit**y

Once the start of injection signal is given, the microcontroller provides an output for the amplifier to drive the piezo stack, but the quantity of fuel provided at each injection also needs to be accurately dosed, and this is accomplished by controlling the so called “injection quantity”, which depends directly on three different parameters:

- The injector physical characteristics: basically this is the nozzle configuration, in other words the amount of spray holes and their diameters. This determines how much fuel the injector can pass per unit of time, when the feeding pressure is kept constant (ideal case) or the pressure drop due to injection (real case) is limited under some tolerable values (this is achieved by a good design not only of the injector but of the whole injection system’s hydraulic aspects).

- The injection duration: the time that elapses between the opening of the needle (which can occur with some delay compared to the start of injection signal) and the instant when fuel no longer is sprayed by the injector (this is ideally coincident with the closing of the needle, but there is anyway a maximum amount of fuel that can be passed, even if the needle gets stuck open, before the flow-fuse valves shut and forces the injection to stop). The flow fuse valve is always dimensioned for allowing the maximum quantity the engine might need at most (110% load) and therefore in a system that works correctly the duration always depends on the needle actions in practise. The delays between the electrical signal and the actual effect of it can be taken care of by some compensation parameters in the electrical side (see *Attachments 8, 9, 10*).

- The injection rate shape: a square injection profile where the fuel pressure gets instantaneously to the maximum value at the start of the injection and is kept at the same value for all the duration, until the needle is shut closed (see Figure 3), will of course see more fuel passing compared to a profile where for example the fuel is fed at half of the maximum pressure for the first half of the total duration, and only in the second half of the total duration the pressure steps up to the maximum value (see Figure 5).

The strategy to control the injection quantity is to keep two of these parameters constant throughout the engine operation (one is fixed, as it depends on the injector's construction, and the other, the injection rate shape, is selected for each engine run and not changed on-the-fly) and to only act on the remaining one, the duration in time.

See *Attachments 8, 9, 10*.

5 CONCLUSIONS

See *Attachment 11.*

6 FURTHER IMPROVEMENTS

See *Attachment 12.*

7 REFERENCES

[1] Jay, D., Delneri, D., Cavressi, F.: “Latest fuel injection systems on medium speed engines used for IMO tier 3 requirements in 2016”, IMechE Conference, London, 2012, pp. 89-102, ISBN 978-0-85709-210-6.